Three-dimensional coupled-wave theory for photonic-crystal surface-emitting lasers(Digest_要約)

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This thesis is devoted to the construction of a three-dimensional (3D) coupled-wave theory (CWT) model for photonic-crystal surface-emitting lasers (PCSELs). Instead of simply extending the previous two-dimensional (2D) CWT model, we have built a new 3D model that analytically describes the complex wave interaction in a full 3D system. The capability of our 3D model is far beyond that of the previous 2D model and conventional numerical computer simulations such as the plane-wave expansion method (PWEM) and the finite-difference time-domain method (FDTD). Our theory is able to treat PC geometries of any arbitrary shape in the PC plane, any lattice structure that enables 2D resonance, and arbitrarily tilted sidewalls. We have demonstrated the efficiency, accuracy, and validity of our theory by comparing it with the numerical simulations and experimental results. Moreover, the modal properties that can be treated are not limited to the threshold condition, but have been extended to the above-threshold regime. The thesis consists of seven Chapters including Introduction and Conclusions, as well as Appendices, Acknowledgments, and List of publications. The following gives a brief description of each Chapter.

Chapter 1 introduces the research background including the unique features and important functionalities of PCSELs that have been experimentally demonstrated thus far. Next, we review the theoretical studies that have been devoted to PCSELs and emphasize the importance of developing an analytical 3D model for this type of laser. Finally, the objective of this thesis is presented.

Chapter 2 introduces the fundamentals of PCSELs including basic laser structures, lasing principles, and theoretical methods. After briefly describing the PCSEL device structures, we explain the formation of a 2D cavity mode based on the Bragg diffraction at the band-edge modes and the threshold conditions of the laser cavity. Next, we give an overview of theoretical methods that have been used for modeling PCSEL cavities including 2D PWEM, 3D FDTD method, and 2D CWT. Limitations of each method are mentioned.

Chapter 3 presents the derivation of 3D CWT and relevant analysis results. Starting from the E-field-based Maxwell's equations, we derive analytical coupled-wave equations by considering a full 3D structure. In contrast to the previous 2D CWT, in the new 3D model we incorporate a large number of high-order waves and the field profiles in the vertical direction. Then, we present the calculated in-plane and vertical field profiles based on the analytical solutions of the individual partial waves. Next, the effect of high-order partial waves on the mode frequency and radiation constant properties is discussed. Finally, we verify the accuracy and validity of the 3D CWT by comparing with 3D FDTD. The fundamental difference between the 2D and 3D systems is also discussed.

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Chapter 4 presents the coupled-wave analysis of a finite-size laser cavity and its comparison with experiments. First, we derive coupled-wave equations for finite-size structures by taking into account of the envelope functions of Bloch waves within an actual laser structure. Then, we use the derived formulation to study various modal properties including threshold gains, resonant mode frequency, near- and far-field patterns (FFPs), polarization profile, etc. The analysis results are compared with experiments to confirm the validity of our analysis. Next, we discuss the finite-size effect on mode selectivity by calculating threshold gain dependence on device size, and further perform experiments to confirm the theoretical predictions. Finally, towards single-mode high-power PCSELs, we study single-mode stability in large-area PCSELs and discuss key factors that affect mode stability.

Chapter 5 is devoted to developing a more general theory that is able to treat a larger family of photonic crystal structures. Two extensions are presented. The first extension is intended for the analysis of triangular-lattice PCs with C_{6v} symmetry. We derive a generalized form of 3D coupled-wave equations in which six basic waves and the direct 2D couplings are introduced. We then calculate the modal properties of interest including the band structure, radiation constant, threshold gain, FFPs, mode selection dependence on air-hole size, etc. These calculated results are compared with experiments. Next, the generalized coupled-wave equations are used to study a more general centered-rectangular lattice that has C_{2v} symmetry. The second extension, arbitrary sidewall shape in the vertical direction, presumes the cases where sidewalls of the fabricated PC air holes are tilted in a dry etching process or exhibit more complicated geometries in a crystal regrowth process. The key modification in the formulation is the incorporation of the refractive index variation in the vertical direction. As an example, we study the radiation properties of PC air holes with tapered and tilted sidewalls, and verify the extended analysis by comparison with 3D FDTD. Additionally, we discuss the influence of different sidewall geometries on radiation properties.

Chapter 6 deals with the laser behavior in the above threshold regime. The theory described in previous Chapters basically applies to situations at or near the laser threshold. Far above threshold, however, the spatial hole burning (SHB) effect resulting from the complex interaction between photons and carriers must be taken into account. We describe the SHB phenomenon and the resulting spatial variation in refractive index and optical gain. Next, we attempt to derive an above-threshold coupled-wave equation by incorporating the nonuniformity in both refractive index and spatial gain. A numerical algorithm for solving the derived nonlinear coupled-wave equations is described. Finally, the above-threshold analysis results are presented by investigating threshold gain dependence on injection current. Effect of SHB on the threshold gain and mode stability is discussed.

Chapter 7 summarizes findings obtained in this thesis and presents perspectives on future work.